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Methods of Measurement for Semiconductor Materials, Process Control, and Devices

Quarterly Report

April 1 to June 30, 1971

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Methods of Measurement for Semiconductor Materials, Process Control, and Devices

Quarterly Report

April 1 to June 30, 1971

Edited by W. Murray Bullis

Electronic Technology Division
Institute for Applied Technology
National Bureau of Standards
Washington, D.C. 20234

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FOREWORD

The Joint Program on Methods of Measurement for Semiconductor Materials, Process Control, and Devices was undertaken in 1968 to focus NBS efforts to enhance the performance, interchangeability, and reliability of discrete semiconductor devices and integrated circuits through improvements in methods of measurement for use in specifying materials and devices and in control of device fabrication processes. These improvements are intended to lead to a set of measurement methods which have been carefully evaluated for technical adequacy, which are acceptable to both users and suppliers, which can provide a common basis for the purchase specifications of government agencies, and which will lead to greater economy in government procurement. In addition, such methods will provide a basis for controlled improvements in essential device characteristics, such as uniformity of response to radiation effects.

The Program is supported by the National Bureau of Standards,* the Defense Atomic Support Agency,† the U. S. Navy Strategic Systems Project Office,§ the U. S. Navy Electronics Systems Command,† the Air Force Weapons Laboratory,¶ the Air Force Cambridge Research Laboratories,# the Advanced Research Projects Agency,× the Atomic Energy Commission,** and the National Aeronautics and Space Administration.†† Although there is not a one-to-one correspondence between the tasks described in this report and the projects by which the Program is supported, the concern of certain sponsors with specific parts of the program is reflected in planning and conduct of the work.

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* Through Research and Technical Services Projects 4251120, 4251123, 4251126, 4252114, 4252119, 4252128, 4254111, 4254112, and 4251115.

† Through Order EA071-801. (NBS Project 4259522).

§ Administered by U. S. Naval Ammunition Depot, Crane, Indiana through Project Orders PO-1-0030, PO-1-0041, and PO-1-0067, and Naval Avionics Facility through Work Request WR-1-1038. (NBS Projects 4259533 and 4254432).

† Through Project Order PO-1-1057. (NBS Project 4252534).

¶ Through Delivery Order F29601-71-F-0002. (NBS Project 4252535).

Through Project Order Y71-906. (NBS Project 4251536).

× ARPA Order 1889 Monitored by Space and Missile Systems Organization under MIPR FY76167100331. (NBS Project 4254422).

**Division of Biology and Medicine. (NBS Project 4259425).

††Through Orders S-70003-G, Goddard Space Flight Center, and H-76553A, Marshall Space Flight Center. (NBS Projects 4254429 and 4251449).

METHODS OF MEASUREMENT FOR SEMICONDUCTOR MATERIALS, PROCESS CONTROL, AND DEVICES

Quarterly Report
April 1 to June 30, 1971

This quarterly progress report, twelfth of a series, describes NBS activities directed toward the development of methods of measurement for semiconductor materials, process control, and devices. Significant accomplishments during this reporting period include a demonstration of the high sensitivity of the infrared response technique by the identification of gold in a germanium diode doped to a level of 10^{11} gold atoms per cubic centimeter, verification that transient thermal response is significantly more sensitive to the presence of voids in die attachment than steady-state thermal resistance, and development of a simplified circuit for screening transistors for susceptibility to hot-spot formation by the current-gain technique. Work is continuing on measurement of resistivity of semiconductor crystals; study of gold-doped silicon; specification of germanium for gamma-ray detectors; evaluation of wire bonds and die attachment; measurement of thermal properties of semiconductor devices, transit time and related carrier transport properties in junction devices, and electrical properties of microwave devices; and characterization of silicon nuclear radiation detectors. Supplementary data concerning staff, standards committee activities, technical services, and publications are included as appendixes.

Key Words: Alpha-particle detectors; aluminum wire; base transit time; carrier lifetime; die attachment; electrical properties; epitaxial silicon; gamma-ray detectors; germanium; gold-doped silicon; methods of measurement; microelectronics; microwave devices; nuclear radiation detectors; probe techniques (a-c); resistivity; semiconductor devices; semiconductor materials; semiconductor process control; silicon; thermal resistance; thermographic measurements; ultrasonic bonder; wire bonds.

1. INTRODUCTION

This is the twelfth quarterly report to the sponsors of the Joint Program on Methods of Measurement for Semiconductor Materials, Process Control, and Devices. It summarizes work on a wide variety of measurement methods that are being studied at the National Bureau of Standards. Since the Program is a continuing one, the results and conclusions reported here are subject to modification and refinement.

The work of the Program is divided into a number of tasks, each directed toward the study of a particular material or device property or measurement technique. This report is subdivided according to these tasks. Highlights of activity during the quarter are given in Section 2. Section 3 deals with tasks on methods of measurement for materials; Section 4, with those on methods of measurement for process control; and Section 5, with those on methods of measurement for devices. References for each section are listed in a separate subsection at the end of that section.

The report of each task includes the long-term objective, a narrative description of progress made during this reporting period, and a listing of plans for the immediate future. Additional information concerning the material reported may be obtained directly from individual staff members connected with the task as indicated throughout the report. The organization of the Joint Program staff and telephone numbers are listed in Appendix A.

An important part of the work that frequently goes beyond the task structure is participation in the activities of various technical standardizing committees. The list of personnel involved with this work given in Appendix B suggests the extent of this participation. Additional details of current efforts in this area are given in Section 2.

Background material on the Program and individual tasks may be found in earlier reports in this series as listed in Appdndix D. From time to time, publications that describe some aspect of the program in greater detail are prepared. Current publications are also listed in Appendix D.

2. HIGHLIGHTS

Significant accomplishments during this reporting period include a demonstration of the high sensitivity of the infrared response technique by the identification of gold in a germanium diode doped with 10^{11} gold atoms per cubic centimeter, verification that transient thermal response is significantly more sensitive to the presence of voids in die attachment than steady-state thermal resistance, and development of a simplified circuit for screening transistors for susceptibility to hot-spot formation by the current-gain technique. Highlights of these and other technical activities are presented in this section; details are given in subsequent sections of the report. This section concludes with a summary of standardization activities being carried out by program staff members.

Resistivity — Principal emphasis was placed on completion of measurements on wafers with chem-mechanically polished surfaces in the study of the effect of current level and probe force on resistivity as measured by the four-probe method and on coordination and analysis of round-robin interlaboratory tests being conducted in cooperation with ASTM Committee F-1 on Electronics. In other work evidence was found that suggests that the difficulty encountered in fabrication of diodes that are satisfactory for capacitance-voltage measurements is due to crystal defects that might be introduced during wafer preparation or during subsequent processing steps. Work in support of spreading resistance methods continued with further efforts to obtain high-quality scanning electron microscope photomicrographs of probe damage to silicon.

Gold-Doped Silicon — Work continued in preparing and evaluating gold-doped silicon wafers in the extensive series of measurements of resistivity, Hall coefficient, and gold concentration outlined previously. Results of the study of lateral uniformity of diffused gold as determined by x-ray fluorescence with the scanning electron microscope suggest either that the clusters which form do not extend as much as 5 μm below the surface or that the gold concentration in a cluster decreases rapidly with distance below the surface. Preliminary measurements of carrier diffusion length by the surface photovoltage technique were attempted on gold-diffused Hall bars.

Specification of Germanium — Study of methods for measuring lithium-ion drift mobility in germanium has been completed with the adoption by ASTM Committee F-1 of a method based on technology developed under this task. Work on methods for measuring carrier trapping in germanium is continuing in cooperation with the committee. The improved infrared response technique was used to study eight germanium diodes; gold was identified in one doped with 10^{11} gold atoms per cubic centimeter. Application of the infrared response method to silicon devices continued.

Die Attachment Evaluation — Modification of the die attachment evaluation equipment to increase its power handling capabilities and to increase the resolution of the digital voltmeter resulted in improved reproducibility of the measurements. Transient thermal response measurements

for a heating-power pulse width of about 10 ms were shown to be more sensitive to the presence of 10-, 20-, and 40-percent void areas in diode die attachment than steady-state thermal resistance measurements. For the particular device tested, a 10-percent void area appears to be the smallest that can be detected by the thermal response technique; it is not detectable by the thermal resistance technique.

Wire Bond Evaluation — Work progressed on ribbon-wire bonding despite several continuing problems with both the bonding machine and the dimensional uniformity of the wire. Scanning electron microscope photomicrographs were made of bonds and of lift-off patterns. Evaluation of the pull test on round-wire bonds was deferred due to serious mechanical problems with the round-wire bonding machine. A simple technique for refinishing used bonding tools was devised. Assistance in the organization of a section on microelectronic bonding was provided in conjunction with the summer meeting of ASTM Committee F-1 at NBS. More than 40 representatives of device manufacturers, materials and equipment producers, and consumers attended. Ten areas in bonding were selected and task forces were set up to take the necessary action.

Processing Facility — Principal effort is being expended on development of a process for fabricating diffused silicon diodes required in the resistivity task for the purpose of measuring resistivity as a function of depth in bulk and epitaxial silicon wafers by the capacitance-voltage method.

Thermal Properties of Devices — Prototype circuits to measure transistor thermal resistance and common-emitter current gain in the common-base operating mode were designed and built. These circuits are much simpler than the common-emitter circuits used up to this point because it is not necessary to use special circuitry in the base lead to control the collector current. In the case of the current-gain measurement, the simplicity of the common-base circuit makes feasible a production-oriented current-gain screening technique for hot-spot formation. In a comparison of the effectiveness of the use of base-emitter junction voltage as a screen for thermal instabilities with that of the common-emitter current gain it was found that while both were sensitive to constricted hot-spots that exhibit thermal hysteresis the former was much less sensitive to the more amorphous, less constricted hot-spots that occur under higher current, lower voltage operating conditions. A study was undertaken to determine the pulse conditions under which a power transistor could be put into a constricted operating mode with thermal hysteresis. With repetitively pulsed collector excursions, it was found that hysteresis occurred when the product of the magnitude of the voltage pulse and the duty cycle was equal to the steady-state voltage change required to initiate hysteresis from a given collector voltage below the d-c hot-spot initiation voltage. For singly pulsed excursions from various collector voltages below the d-c hot-spot initiation voltage, it was found that, for a given pulse width, the combined d-c and pulsed voltage

required to initiate hot-spots increased as the starting d-c collector voltage level was reduced.

Microwave Device Measurements — To improve the precision of the low intermediate-frequency conversion-loss measurements, an incremental modulation technique has been introduced. With this technique, precision is limited principally by the resolution of the attenuator used to set the increment and by the mechanical stability of the waveguide system rather than by the output resolution.

Carrier Transport in Junction Devices — The vector-voltmeter measurement system for measuring transistor delay time was assembled and preliminary tests were carried out. Two systems for the measurement of transistor S-parameters in the 200 to 800 MHz range are being assembled. An analysis of the equivalent circuits of a transistor in the Sandia-type bridge and in the vector-voltmeter circuit has been made to relate the measured delay time to various time constants and delay times within the device.

Silicon Nuclear Radiation Detectors — Study of radiation damage effects of 600-keV electrons and fast neutrons in lithium-drifted silicon detectors has been completed. A preliminary study of the effect of exposure of a silicon surface-barrier detector to dry ammonia and methanol vapor at various pressures was completed. No significant changes in noise level were observed during these tests.

Standardization Activities — Many of the standardization activities undertaken by program staff are broader than the technical tasks described in the following sections. These activities involve general staff support in committees, coordination of efforts which may encompass a variety of tasks, and participation in areas where no direct in-house technical effort is underway. Standardization activities directly related to particular task areas are reported with the appropriate tasks. A summary of standardization and dissemination activities during FY 1971 is given in Appendix E.

Twelve program staff members attended the regular summer meeting of ASTM Committee F-1 held at the NBS facilities in Gaithersburg. Program staff members were instrumental in the organization of a new section on Bonding of Subcommittee 7 on Hybrid Microelectronics (see Section 4.2). Mrs. K. O. Leedy was appointed chairman of the section. J. R. Ehrstein was appointed chairman of the Resistivity Section of Subcommittee 6 on Electrical Measurements. W. M. Bullis was appointed member-at-large to the Advisory Committee.

Activity in connection with JEDEC committees of the Electronic Industries Association continued in a variety of areas. Contact with the chairman of Committee JC-21 on UHF and Microwave Diodes was renewed in order to discuss the status of the microwave diode task and its relation

to current industry requirements. F. F. Oettinger attended meetings of Committees JC-22 on Rectifier Diodes and Thyristors and JC-11 on Mechanical Standardization.

W. M. Bullis was appointed to the Planning Subcommittee of SAE Committee H on Electronic Materials and Processes. F. F. Oettinger was appointed to the Technical Program Committee for the March 1972 IEEE International Convention.

3. METHODS OF MEASUREMENT FOR SEMICONDUCTOR MATERIALS

3.1. RESISTIVITY

Objective: To develop methods suitable for use throughout the electronics industry for measuring resistivity of bulk, epitaxial, and diffused silicon wafers.

Progress: Principal emphasis was placed on completion of measurements on wafers with chem-mechanically polished surfaces in the study of the effect of current level and probe force on resistivity as measured by the four-probe method, and on coordination and analysis of round-robins being conducted in cooperation with ASTM Committee F-1 on Electronics. In other work, evidence was found that suggests that the difficulty encountered in fabrication of diodes that are satisfactory for capacitance-voltage measurements is due to crystal defects that might be introduced during wafer preparation or during subsequent processing steps. Work in support of spreading resistance methods continued with further efforts to obtain high-quality scanning electron microscope photomicrographs of probe damage to silicon. Study of probe impact momentum was deferred.

Four-Probe Method — Measurements were completed on seven silicon wafers with chem-mechanically polished surfaces in the study to determine the effect of current level and probe force on the measurement of resistivity by the four-probe method. The procedure used was identical to that used previously on mechanically polished slices (NBS Tech. Note 598, p. 7). Preliminary examination of the results suggests that the form of the current and probe-force dependence is virtually unchanged between the mechanically polished and chem-mechanically polished surfaces on the same wafer. However, at any specific combination of current and probe force the resistivity measured on the chem-mechanically polished surface is lower by 0.5 to 1.5 percent than that on the same wafer with a mechanically polished surface. (J. R. Ehrstein and D. R. Ricks)

An auxiliary study has been started to try to relate variation in measured resistivity with surface condition to amount of subsurface damage. Measurements of carrier diffusion length by the surface photovoltage method have been found to be sensitive to the nature of the specimen surface. Surface photovoltage measurements are being made on specimens with lapped, mechanically polished, and chem-mechanically polished surfaces to determine qualitatively the extent of subsurface damage.
(J. R. Ehrstein, W. R. Thurber, W. E. Phillips, and A. W. Stallings)

Standardization Activities — A summary of the results of the round-robin on four-probe measurement of resistivity of silicon wafers in the 5,000 to 20,000 Ω·cm range was presented to the Resistivity Section of Committee F-1 at its June meeting. Seven laboratories participated in the round-robin. Five silicon specimens and two analog resistance boxes [1] were circulated. Two *p*-type and one *n*-type specimen had room-temperature (23°C) resistivity around 6,000 Ω·cm; one *n*-type and one

p-type specimen were supplied as 14,000 to 15,000 Ω•cm. The analog boxes used for calibration had standard resistors of 1,000 and 10,000 Ω.

No serious difficulties were encountered in measurement of the analog boxes; with resistors 300 times as large as the standard resistor in both the current and potential leads, the maximum error in measuring the resistance of the standards was ±1.5 percent. Measurement of the 6,000-Ω•cm *n*-type specimen resulted in a sample standard deviation of 3 to 4 percent, well within the precision quoted for wafers with resistivity between 500 and 2,000 Ω•cm [1]. Measurement of the 6,000-Ω•cm *p*-type specimens and of both the higher resistivity specimens resulted in sample standard deviations greater than 10 percent, considerably outside the precision quoted for lower resistivity specimens [1].

Preliminary results of the round-robin on four-probe measurement of resistivity of silicon epitaxial layers deposited on substrates of opposite conductivity type were also presented at the June meeting of Committee F-1. Seven of the eleven scheduled participants had completed their measurements. The results are being reviewed to determine whether they are sufficient to support a precision statement in the standard method now under development for this test.

Capacitance-Voltage Method — Arrays of 20- and 30-mil (0.5- and 0.75-mm) diameter diodes were fabricated in four 15-Ω•cm, *n*-type silicon slices by means of the same fabrication procedure previously used on 1 Ω•cm slices (see Section 4.3). Measurements of capacitance as a function of voltage (C-V) were inhibited by insufficiently large breakdown voltages on most of the diodes on the four wafers. Microscopic inspection of these wafers revealed a pattern of linear defects present on most of the devices on all four wafers. On each wafer all the linear defects were oriented in the same direction over the entire wafer surface. It was also found that those few diodes which had acceptable breakdown voltages were characterized by an absence of these defects. All diodes that could be measured were located near the edge of the wafer where the four-probe resistivity values were not reliable so that valid comparison between C-V and four-probe data was impossible. At present the various steps in the processing procedure are being scrutinized to try to determine the origin of these defects so that the procedure can be modified to produce a greater yield of diodes with acceptable breakdown voltages.

Preliminary measurements were made on 20-mil (0.5-mm) diameter, 0.5 μm deep, boron-diffused, mesa diodes obtained from another laboratory in order to gain additional information concerning the C-V measurement system and to provide data for use during the development of analytical procedures. (R. L. Mattis)

Spreading Resistance Method — Attempts to use the scanning electron microscope to study probe impact damage on silicon are continuing. Emphasis is on reproducible production of photomicrographs of extremely high quality similar to those which were made on a recent occasion with

magnifications up to 17,000 X. Work is in progress to produce a silicon specimen that can be used to qualify the SEM system for high resolution on any given occasion before proceeding with the specimen of interest.

(J. R. Ehrstein)

Plans: Study of the current-level and probe-force dependence of four-probe resistivity measurements will be continued with measurements of resistivity on lapped surfaces in order to compare with resistivity values measured on this surface finish at the beginning of the study. Detailed statistical analysis of the data obtained in the study will begin. To estimate the amount of subsurface damage caused by various processing steps the series of surface photovoltage measurements on wafers with the same surface preparations as in the four-probe resistivity study will be continued. An attempt to relate the extent of surface damage to the observed shift in measured resistivity between mechanically and chem-mechanically polished slices will be made. Experiments will be performed to determine whether the surface defects which reduce diode yield are caused by the wafer processing. Development of procedures for analyzing the results of C-V measurements will continue. Work on use of the scanning electron microscope to examine probe damage on silicon will continue. Work will also resume on use of a piezoelectric transducer to study impact momentum of various configurations of a spreading resistance probe.

3.2. GOLD-DOPED SILICON

Objective: To characterize *n*- and *p*-type silicon doped with gold and to develop a model for the energy-level structure of gold-doped silicon which is suitable for use in predicting its characteristics.

Progress: Hall effect and resistivity measurements were made at room temperature on Hall bars cut from 10-, 20-, and 90-Ω·cm *p*-type wafers diffused with gold at various temperatures. The gold concentration in each of the wafers had been determined by neutron activation analysis. These results are shown in figure 1. For comparison, resistivity calculated from an energy-level model for gold-doped silicon is also shown in figure 1. In these calculations the energy of the gold donor and acceptor were taken as 0.35 eV above the valence band and 0.54 eV below the conduction band, respectively [1], the degeneracy factors were taken as 0.25 for the donor and 1.5 for the acceptor [2], and the energy gap and effective masses were taken from the work of Barber [3]. The calculation is based on a solution to the charge balance equation to find the Fermi level and, hence, the hole concentration. Lattice mobility [4] and impurity mobility [5] were combined reciprocally to obtain the hole mobility used in the calculation of the resistivity.

Experimentally it was found that the resistivity decreases at large gold concentration, whereas the theory predicts a continual increase in resistivity with gold concentration. Hall measurements confirm that the

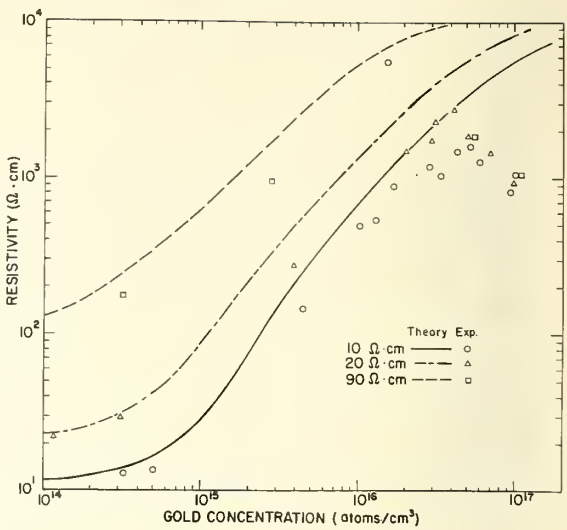

Figure 1. Resistivity as a function of gold concentration in *p*-type silicon. (Error bars are not indicated. The standard deviation of the gold determination is estimated to be about 10 percent. Resistivity values are reproducible within about 5 percent).

retrograde behavior is due to an increase in the charge carrier density rather than an increase in the carrier mobility. A suitable model to explain this behavior has not yet been found.

Gold diffusions were completed on sets of *n*-type wafers with initial room temperature (23°C) resistivity of 5, 80, 400, and 2,200 Ω•cm. The diffusion temperatures and times used were: 850°C for 288 h, 950°C for 144 h, 1050°C for 72 h, 1150°C for 24 h, and 1250°C for 8 h. Gold concentrations were determined by activation analysis. Data on these and previous sets of wafers indicate that the diffusion times at 1150 and 1250°C are long enough that the concentration of gold reaches the solubility limit [6], but the times at the lower temperatures are not long enough for this to occur.

(W. R. Thurber, A. W. Stallings, T. F. Leedy, and W. M. Bullis)

A layer 5-μm thick was removed by lapping from the surface of the Hall bar previously shown to have gold clusters by x-ray fluorescence (NBS Tech. Note 598, p. 13). In all regions, including those where clusters had been observed, the x-ray intensity of the gold peak did not exceed the background level. This suggests either that the clusters do not extend as much as 5 μm below the surface or that the gold concentration in a cluster decreases rapidly with distance below the surface.

(W. J. Keery and W. R. Thurber)

Preliminary measurements of carrier diffusion length were attempted on gold-diffused Hall bars. Difficulties were encountered that can be traced to low signal levels; modifications to the equipment to overcome these limitations were begun. (W. R. Thurber and W. E. Phillips)

Plans: A new specimen holder will be fabricated for room temperature Hall effect and resistivity measurements. Improved means for maintaining and measuring the specimen temperature will be included. Electrical properties of the Hall bars cut from the 5-, 80-, 400-, and 2,200-Ω·cm *n*-type, gold-diffused wafers will be measured using the new holder. Sets of *p*-type wafers with room temperature (23°C) resistivities of 0.5, 1,000, and 2,000 Ω·cm will be diffused with gold at five temperatures from 850 to 1250°C.

To further study the retrograde behavior of the resistivity in *p*-type material, 10-Ω·cm wafers will be diffused at 1250°C for 8, 16, 32, and 64 hours. These times are all long enough for the gold concentration to stabilize at its maximum solubility, but if foreign impurities are diffusing in, their concentration should increase with time and change the measured resistivity.

Additional measurements of carrier diffusion length will be made by the surface photovoltage method on the same Hall bars used for electrical measurements after modifications to the equipment have been completed.

3.3. SPECIFICATION OF GERMANIUM

Objective: To measure the properties of germanium crystals and to correlate these properties with the performance of germanium gamma-ray detectors in order to develop methods for the early identification of crystals suitable for fabrication into lithium-compensated gamma-ray detectors.

Progress: Study of methods for measuring lithium-ion drift mobility in germanium has been completed with the adoption by ASTM Committee F-1 of a method based on technology developed under this task [1]. Work on methods for measuring carrier trapping in germanium is continuing in cooperation with the committee. The improved infrared response technique was used to study eight germanium diodes; gold was identified in one that had been doped to a concentration of 10^{11} gold atoms per cubic centimeter. Application of the infrared response method to silicon devices continued.

Characterization of Germanium — Measurements of carrier trapping have been completed on specimens from two germanium crystals. The procedure used was that specified for the second round-robin being conducted in cooperation with the Germanium Section of Committee F-1. Detector resolution was measured as a function of applied electric field using the 1333-keV gamma ray of ^{60}Co. The position (channel number) of the center of the 1333-keV peak in the pulse-height spectrum was also determined as a function of bias; independent values of effective carrier lifetime in the test specimens can be obtained from the results of the two measurements. An additional series of measurements was carried out using a collimated beam of 662-keV gamma rays from ^{137}Cs in order to calculate

values of carrier lifetime using a model for carrier trapping developed in this laboratory [2] and compare them with the values obtained according to the round-robin procedure.

(W. J. Keery, H. E. Dyson, and A. H. Sher)

Germanium Detector Measurements — Detectors fabricated from specimens of eight germanium crystals were examined by the infrared response (IRR) technique. IRR spectra obtained from three germanium diodes for the energy range 0.5 to 0.7 eV using a 640-line per millimeter grating and a 1-mm thick germanium filter window are shown in figure 2. The spectrum of NBS-83-3, a lithium-drifted diode, is typical of germanium used for fabricating good quality gamma-ray detectors of this type. The spectrum of NBS-112, a diode* fabricated from a specimen of high-purity germanium with an initial net donor concentration of approximately 7×10^{10} cm^{-3} is in general similar to that of NBS-83-3 except that structure is not observed at either 0.50 or 0.52 eV. Since lithium compensation was not used in the fabrication process (NBS Tech. Note 598, pp. 15-16) one would not expect to observe the 0.50-eV level due to the lithium-defect interaction. Structure in the region near 0.52 eV has been noted in all lithium-drifted diodes; some of the defects responsible for this structure apparently are not present in the high-purity crystals. The spectrum of NBS-113, a diode* fabricated from a crystal of high-purity germanium intentionally doped with approximately 10^{11} gold atoms per cubic centimeter, exhibits peaks at 0.57 and 0.66 eV. Gold introduces a donor level at an energy of $E_v + 0.05$ eV, and acceptor levels at $E_v + 0.15$, $E_c - 0.20$ and $E_c - 0.04$ eV in germanium [3]; the peaks in the spectrum can be related to the excitation of electrons from the donor level and the lowest acceptor level to the conduction band. These results demonstrate the high sensitivity of the IRR technique to the presence of gold in germanium.

Attempts were made by measurement of IRR to confirm the presence of iron in NBS-301, fabricated from a germanium crystal† intentionally contaminated with stainless steel during growth from the melt. Levels in germanium arising from iron impurity are at energies of $E_v + 0.34$ eV and $E_c - 0.27$ eV [3]. Observed broadening on the high energy side of the 0.36 eV peak might possibly be due to excitation of electrons from the lower iron level to the conduction band; however, because of the still unknown origin of peaks observed in germanium at 0.36, 0.24, and 0.18 eV, no definite conclusions can be drawn from the IRR data at present.

(A. H. Sher, W. J. Keery, and H. E. Dyson)

A study was carried out to determine the feasibility of obtaining IRR spectra in digital form for analysis by computer and ease of comparison of spectral runs made at different settings. A method that involved use

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* Supplied by R. D. Baertsch, General Electric Company, Schenectady, N. Y. 12301.

† Supplied by I. L. Fowler, AECL Chalk River Nuclear Laboratories, Chalk River, Ontario, Canada.

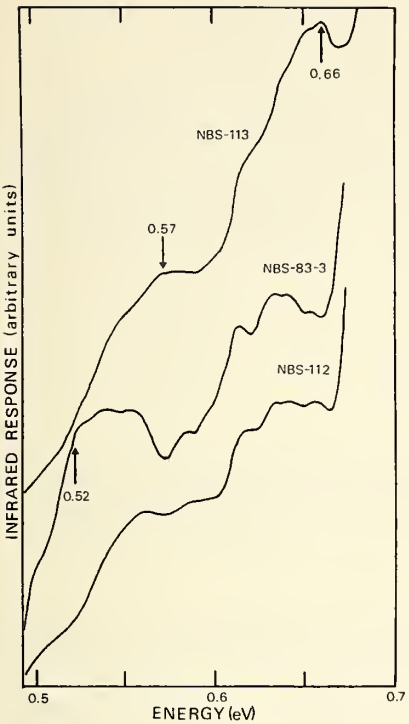

Figure 2. Infrared response spectra of three germanium gamma-ray detectors.

of equipment currently on hand was found to be successful. The varying voltage output from the phase-sensitive amplifier is converted linearly to a variable frequency and fed to a miltichannel analyzer that is operating in the multiscaling mode in which total counts occuring in a given time interval are stored in one channel. A switch mounted on the monochromator grating drive to give 100 closures per drum turn advances the analyzer address so that the recorded count is proportional to the IRR signal at any given energy. The IRR spectrum in digital form is then punched onto paper tape and analyzed by a computer. (W. J. Keery and A. H. Sher)

Further efforts were made to apply the IRR technique to microelectronic devices (NBS Tech. Note 598, p. 16) by studying a 37-mil (0.94-mm) square silicon mesa diode mounted on the special right-angle holder at the end of the cryostat cold finger. Although considerable improvement in signal-to-noise ratio was obtained by using a 0.1-mm thick silicon filter and by replacing the 45-W light source with a 150-W light source, only the band-edge peak was observed. The present effort was also hampered by development of mechanical problems in the motorized monochromator grating drive. (W. J. Keery)

Plans: Emphasis will continue on the interpretation of results obtained using the improved IRR technique. Efforts to extend this technique to silicon microelectronic devices will continue. As this effort has been expanded to include silicon devices and detectors as well as those of germanium, subsequent results will be reported in a section of future quarterly reports devoted to infrared methods. The monochromator drive mechanism will be repaired, the 100-closure per drum turn switch installed, and the monochromator recalibrated. Measurements of IRR on lithium-drifted silicon detectors subjected to electron and neutron radiation damage (see Section 5.5) will begin.

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4.1. DIE ATTACHMENT EVALUATION

Objective: To evaluate methods for detecting poor die attachment in semiconductor devices with initial emphasis on the determination of the applicability of thermal measurements to this problem.

Progress: Measurements of steady-state and transient thermal response of diodes with various size voids reported previously (NBS Tech. Note 598, p. 20) indicated that the increase in sensitivity to voids of the transient thermal response measured for power pulses of 7 and 9 ms over that of the steady-state thermal response ranged in most cases from 90 to 700 percent. The data also indicated that although the spread in measured junction-to-case temperature difference, ΔT_{JC}, was small for devices with no intentional voids this was not the case with the intentionally voided devices. These conclusions are illustrated in figures 3 and 4 which show transient thermal response curves for a representative sampling of devices. Curves denoted by the symbol HV or IV are for diodes that had a void area introduced into the die attachment while curves denoted by the symbol H or I are for control diodes without voids. The voided devices, series HV and IV, were bonded on gold-plated TO-5 headers with 20- and 29-mil (0.51- and 0.74-mm) diameter dimples ultrasonically machined into the bonding surface (NBS Tech. Note 560, pp. 27-29) to produce voids that are approximately 20 and 40 percent of the total chip bonding area, respectively. The results presented in these figures generally confirm the anticipated thermal response behavior (NBS Tech. Note 555, pp. 25-27). At heating-power pulse widths greater than about 10 to 20 ms, the increase in ΔT_{JC} due to poor die adhesion is essentially constant; the maximum sensitivity occurs for pulse widths of about 10 ms. The spread in thermal response of the devices with the 20-percent void areas was significantly larger than in that of devices with 40-percent void areas. Radiographs and sectioning of both types of voided devices indicated that the unbonded region around the smaller dimples was larger than expected and varied from diode to diode, while better control was in evidence for devices with the larger dimples.

The die attachment evaluation equipment was modified to increase its power handling capabilities and to increase the resolution of the digital voltmeter that indicates the forward voltage used as the temperature sensitive parameter. Long-term, single-operator measurements were made to recheck the reproducibility of the equipment. Over a period of 9 days, steady-state and transient thermal response for heating-power pulse widths of 7, 10, and 14 ms were measured 12 times each on three commercial silicon mesa diode chips bonded to TO-5 headers. The average value and sample standard deviation of ΔT_{JC} obtained for each measurement condition are listed in table 1. The diode heating current was 800 mA for the pulsed measurements and 300 mA for the steady-state measurements. In all cases

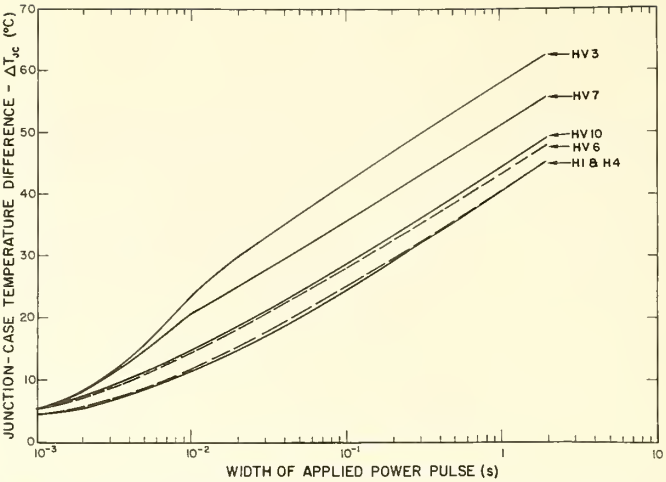

Figure 3. Thermal response curves for diodes with 20-percent void areas and their controls.

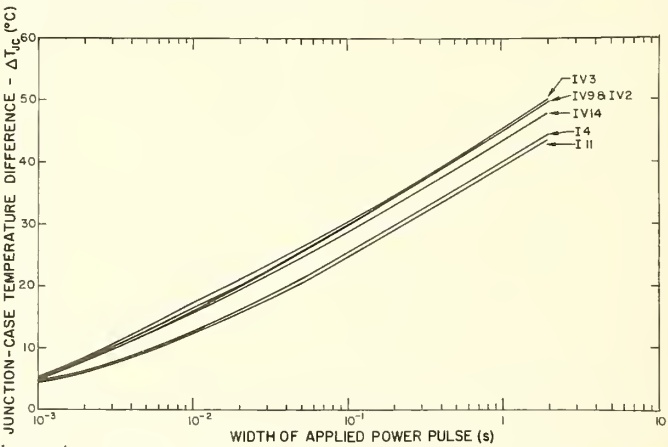

Figure 4. Thermal response curves for diodes with 40-percent void areas and their controls.

Table 1 — Results of Repetitive Junction-to-Case Temperature Difference Measurements after Equipment Improvements

Device No.	Pulse Width 7 ms	10 ms	14 ms	Steady State
I1	10.44±0.28°C	11.86±0.23°C	13.31±0.20°C	14.74±0.15°C
I2	10.86±0.19	12.26±0.20	13.64±0.18	15.36±0.19
I3	9.84±0.10	11.25±0.09	12.63±0.15	14.39±0.24

the forward voltage was measured 50 μs after termination of the heating current. The maximum sample standard deviations of ±0.28°C for the transient thermal response measurements and ±0.24°C for the steady-state measurement were substantially lower than the values of ±0.54°C and ±0.69°C obtained before the circuit was modified (NBS Tech. Note 598, pp. 18-19).

Measurements of steady-state thermal response and transient thermal response for heating-power pulse widths ranging from 1 to 100 ms were made on 10 diodes bonded to gold-plated TO-5 headers with 15-mil (0.37-mm) diameter dimples ultrasonically machined into the bonding surface and on 10 control diodes with no intentional voids. This size dimple produces voids that are approximately 10 percent of the total chip bonding area. The average steady-state thermal response and transient thermal response for a heating-power pulse width of 10 ms, measured on the control diodes 50 μs after the termination of the heating pulse, were 15.53°C and 12.01°C, respectively. A heating current of 800 mA was used for the transient response measurement while 300 mA was used for the steady-state measurement. The sample standard deviations in measured ΔT_{JC} under steady-state and transient conditons were ±0.73°C and ±0.90°C, respectively. This was significantly larger than was observed previously (NBS Tech. Note 598, pp. 19-20) on control devices associated with diodes having 20- and 40-percent void areas. For half of the diodes with voids, ΔT_{JC} measured under transient conditions fell within the scatter obtained on the controls, while the other half showed significantly larger values of ΔT_{JC}. Nevertheless, it can be asserted with 95 percent confidence [1] that the average of the thermal response readings for the diodes with 10-percent void area exceeds the average of the controls, although there is no reason to believe that the average of the steady-state temperature rise exceeds the average of the controls. It appears then, that a 10-percent void in the chip bonding area is the smallest size void that can be detected in this particular device using the transient thermal response technique while a measurement of thermal resistance would not be sensitive to void areas this small. (F. F. Oettinger and R. L. Gladhill)

Plans: Measurements of steady-state and transient thermal response on diodes with controlled void areas of various diameters will continue. Analysis of the accumulated steady-state and transient thermal response data for diodes with the various size voids and their controls will continue. A study will also be undertaken to ascertain, theoretically, the limitations of thermal response techniques for detecting poor die adhesion in the devices under investigation.

4.2. WIRE BOND EVALUATION

Objective: To survey and evaluate methods for characterizing wire bond systems in semiconductor devices and where necessary to improve existing methods or develop new methods in order to detect more reliably those bonds which eventually will fail.

Figure 5. SEM photomicrograph of typical ribbon-wire first bond. (Magnification 350 x)

Figure 6. SEM photomicrograph of typical ribbon-wire second bond. (Magnification 390 x)

Figure 7. SEM photomicrograph of overbonded ribbon-wire first bond. (Magnification 400 x)

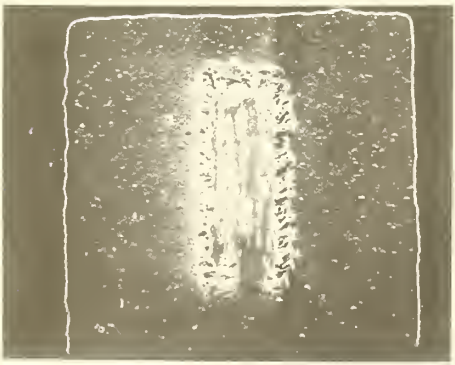

Figure 8. SEM photomicrograph of lift-off pattern of ribbon-wire first bond. (Magnification 350 x)

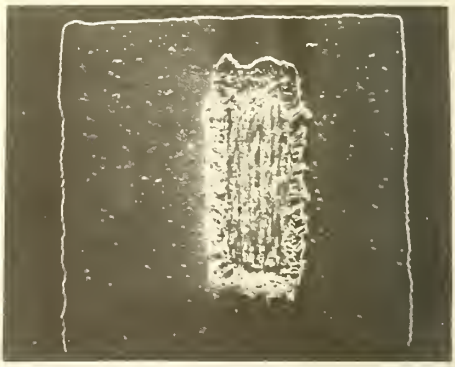

Figure 9. SEM photomicrograph of lift-off pattern of ribbon-wire second bond. (Magnification 350 x)

Progress: Work progressed on ribbon-wire bonding despite several continuing problems with both the bonding machine and the dimensional uniformity of the wire. Scanning electron microscope (SEM) photomicrographs were made of bonds and of lift-off patterns. Evaluation of the pull test on round-wire bonds was deferred due to serious mechanical problems with the round-wire bonding machine. A simple technique for refinishing used bonding tools was devised. Assistance in the organization of a section on microelectronic bonding was provided in conjunction with the summer meeting of ASTM Committee F-1 at NBS. More than 40 representatives of device manufacturers, materials and equipment producers, and consumers attended. Ten areas in bonding were selected and task forces were set up to take the necessary action.

Ribbon-Wire Bonding — Limited work continued on the ribbon-wire bonder received last quarter. Several problems remain to be solved before optimum performance and reliability can be achieved. The most serious problem is that the bonding tool jumps straight up and bounces after the first bond is made. Such motion bends the wire at the heel, causing a crack which weakens the bond. Correction of this motion can only be accomplished by designing a new transducer-motion cam. A considerable variation in bond tail length has also been observed. This must be controlled before the machine can be used to bond devices. In addition the available ribbon wire does not have uniform dimensions. The variations observed on a single spool of wire with cross-sectional dimensions 38 by 12 μm were large enough to cause significant changes in bonding characteristics. Efforts were begun to determine if closer manufacturing tolerances can be achieved.

SEM photomicrographs were made of several ribbon-wire bonds and lift-off patterns in order to understand the way such bonds are formed. A photomicrograph of a typical first bond made with normal power, time, and force settings is shown in figure 5. The crack in the heel can be largly attributed to the vertical jumping motion of the tool after the bond is made. A photomicrograph of a typical second bond also made with normal settings is shown in figure 6. The deformation for each bond is negligible. Figure 7 shows a photomicrograph of a grossly overbonded first bond that was made with twice the power setting of the bond in figure 5. Even in this extreme case the deformation is only about 25 percent. This small deformation is assumed to be the reason why most ribbon bonds break in a pull test at a tensile force in the wire of between 0.7 and 0.9 times the tensile strength of the wire, whether a heel crack is present or not. This is comparable with very good quality round-wire bonds (NBS Tech. Note 598, p. 26). Photomicrographs of lift-off patterns of a first bond and a second bond are shown in figures 8 and 9, respectively. Such patterns are made by reducing the value of one or more bonding parameters, in this case the power, below the point where the wire will stick to the pad. The bonding pattern is similar to those obtained for round-wire (NBS Tech. Note 560, pp. 33-34); the main bonded area is around the perimeter of the bond.

As bonding progresses to the point that the wire will stick, the bonded area extends inward toward the center. (H. K. Kessler)

Technique for Polishing Bonding Tools — A simple and convenient technique for repolishing the bonding face of flat bonding tools has been devised. This technique requires no specialized equipment. A flat copper plate loaded with a diamond-bort paste is placed in the work stage of the bonding machine. The tool is lowered onto this polishing plate by adjusting the search-height control. The tool is polished by moving the work stage under the stationary tool in a general figure-eight pattern while the tool is applied with a force comparable with that used in bonding. During polishing, it is essential that the bonding tool be perpendicular to the diamond-loaded copper plate. The tool is removed and cleaned ultrasonically before it is used for bonding. A preliminary evaluation of the method was carried out with diamond paste commerically specified as 3-μm particle size and by polishing for 1 min. This produced such a highly smooth finish that the tool had to be broken in by making a number of bonds at high power until the finish was slightly degraded. Use of a coarser diamond-bort paste should eliminate the need for this step. (H. K. Kessler)

Standardization Activities — Considerable time was devoted to an organizational meeting to form a new section of Subcommittee 7 of ASTM Committee F-1 to develop standard test methods for microelectronic bonding. The purpose of the initial meeting was to identify areas in bonding where meaningful standards can be written, considering the present technology. More than 40 representatives of device manufacturers, materials and equipment producers, and consumers attended the meeting, chaired by K. O. Leedy. Ten areas in bonding were selected for further investigation: the destructive pull test, wire deformation, visual inspection, the temperature cycling test, the air blast test, bonding wire specifications, bonding tool specifications, tests for metallization adherence and bondability, tests for beam-lead adherence, and a glossary of terms used in microelectronic bonding. Tests discussed but not chosen for further investigation at this time include the non-destructive pull test, the centrifuge test, the ultrasonic vibration test, the mechanical shock test, the shear test, and tests for evaluating flip-chip bonds. Anyone interested in participating in this activity should contact the chairman. (K. O. Leedy and G. G. Harman)

Bibliography and Critical Review — The bibliography was cleared for publication as an NBS Technical Note [1]. Work on the final draft of the critical survey paper continued. (H. A. Schafft)

Plans: Theoretical and experimental work on electronic mixing of bonding tool ultrasonic signals will resume in the effort to better understand and control the bonding process. Advancement of the experimental work is contingent upon acquisition of specialized equipment. Attempts will be made to secure ribbon-wire with closer dimensional tolerances and its evaluation for ultrasonic bonding will continue. Further work on the

wire indentation tester will be deferred until a suitable method for calibration is found. Experimental and statistical analysis of significant factors in the wire bond pull test will resume when the round-wire bonder is repaired and brought under control. Further assistance will be given to sponsors in connection with problems encountered on device production lines. Cooperation with the newly formed Section on Microelectronic Bonding in Committee F-1 will continue with work on defining and evaluating the parameters of the destructive wire bond pull test. Efforts will be made to coordinate this ASTM activity with associated activity in the Society of Automotive Engineers and the Electronic Industries Association. The final draft of the critical survey paper will be completed and prepared for publication as an NBS Technical Note. The preparation of a bibliography of limited distribution reports will be initiated.

4.3. PROCESSING FACILITY

Objective: To establish a microelectronics fabrication laboratory with the facilities and procedures necessary for the production of specialized silicon devices for use in research on measurement methods.

Progress: A process is being developed for fabricating diffused silicon diodes required by the resistivity task for the purpose of measuring the resistivity as a function of depth in silicon bulk and epitaxial wafers by the capacitance-voltage method. The requirements of the diffusion are that its surface concentration be high ($>10^{20}$ cm^{-3}), that the junction be abrupt, and that the junction be shallow (<1 μm). Preparation of the diodes begins with the thermal oxidation of 1- to 10-Ω·cm *n*-type wafers to a thickness of 0.5 μm to form a diffusion mask. Circular windows, 0.5 mm in diameter, are defined in the oxide with conventional photolithographic techniques. After cleaning, the wafer is diffused for 1 h with boron from a boron nitride source at 1050°C. Sections of the diodes are beveled and stained to verify the junction depth. Typically the sheet resistance is 10 Ω/□, giving a surface concentration of approximately 6×10^{20} atoms per cubic centimeter. Diodes prepared in this manner on 1-Ω·cm wafers have exhibited breakdown voltages less than 20 V in contrast to an expected value of 60 V. The origin of the low breakdown voltages is being investigated in cooperation with the resistivity group (see Section 3.1).

Additional effort was expended attempting to improve the quality of aluminum films produced by the electron beam evaporation system. A cryogenic coil was installed in an unsuccessful attempt to getter the gas produced during evaporation. The coil consisted of 5 turns of ¼-in. (6.2-mm) diameter copper tubing bent into a 16-inch (450-mm) diameter helix. Liquid nitrogen passed through the coil served as the refrigerent. No decrease in pressure was noted as the coil was cooled. Efforts were also hampered by leaks around the low temperature connectors.

(T. F. Leedy and J. Krawczyk)

Plans: Groups of diodes required by the resistivity task will be fabricated in an attempt to determine where the defects originate. After each step of the process a wafer will be withdrawn and etched in a preferential etch to display the crystallographic damage induced by that step. Both commercially polished wafers and wafers from a crystal cut and polished in-house will be used.

In the future, fabrication work will be reported with the appropriate task. This section on Processing Facility will not be included unless significant inprovements or additions to the capabilities of the facility have been made.

4.4. REFERENCES

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4.2. Wire Bond Evaluation

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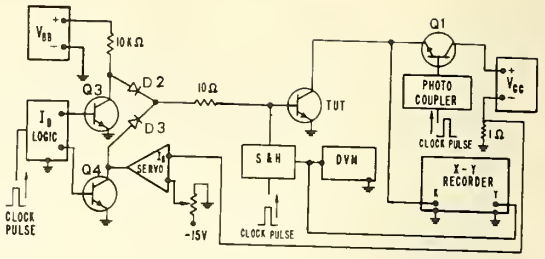
5.1. THERMAL PROPERTIES OF DEVICES

Objective: To evaluate and, if necessary, improve electrical measurement techniques for determining the thermal characteristics of semiconductor devices.

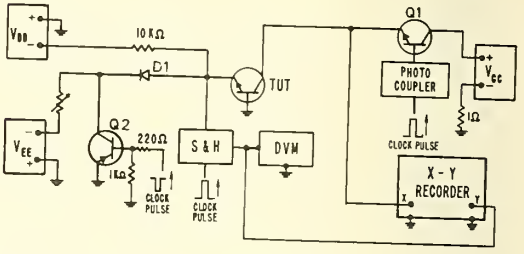
Progress: Prototype circuits to measure transistor thermal resistance and common-emitter current gain in the common-base operating mode were designed and built. These circuits are much simpler than the common-emitter circuits used up to this point because it is not necessary to use special circuitry in the base lead to control the collector current. In the case of the current-gain measurement, the simplicity of the common-base circuit makes feasible a production-oriented current-gain screening technique for hot-spot formation. In a comparison of the effectiveness of the use of base-emitter junction voltage as a screen for thermal instabilities with that of the common-emitter current-gain it was found that while both were sensitive to constricted hot-spots that exhibit thermal hysteresis the former was much less sensitive to the more amorphous, less constricted hot-spots that occur under higher current, lower voltage operating conditions. A study was undertaken to determine the pulse conditions under which a power transistor could be put into a constricted operating mode with thermal hysteresis. With repetitively pulsed collector excursions, it was found that hysteresis occurred when the product of the magnitude of the voltage pulse and the duty cycle was equal to the steady-state voltage change required to initiate hysteresis from a given collector voltage below the d-c hot-spot initiation voltage. For singly pulsed excursions from various collector voltages below the d-c hot-spot initiation voltage it was found that, for a given pulse width, the combined d-c and pulsed voltage required to initiate hot-spots increased as the starting d-c collector voltage level was reduced.

Standardization Activities — The measurement procedure and data collection format were established for the preliminary round robin on thermal resistance being conducted in cooperation with JEDEC Committee JC-25 on Power Transistors. Fourteen test specimens were measured in accordance with the prescribed test procedure and sent to the first of the 10 industry participants. (F. F. Oettinger and S. Rubin)

Thermal Resistance Methods — The study to compare other frequently used thermal resistance measuring methods with the common-emitter base-and-collector switching technique now under investigation (NBS Tech. Note 598, pp. 33 -34) was continued. A prototype circuit to measure transistor thermal resistance, R_θ, in the common-base operating mode was designed and built. The simplified circuit diagrams in figure 10 show both the previously built common-emitter R_θ measuring circuit and the newly designed and fabricated common-base R_θ measuring circuit. In each case the transistor Q1 is initially on, and the sample-and-hold unit is holding. In



a. Common-emitter



b. Common-base

Figure 10. Circuits for measuring thermal resistance of transistors.

the common-emitter circuit, the transistor Q3 is initially on and the transistor Q4 is initially off so that only the I_B servo is providing current to the base of the transistor under test. In the common-base circuit, the transistor Q2 is off and the diode D1 in the emitter lead is conducting. In both cases when the 120-μs wide, 4-pps clock pulse is applied, the transistor Q1 is turned off by means of the photo coupler, and the sample-and-hold unit samples the emitter-to-base voltage for approximately 1 μs at the end of a 10-, 20-, 50-, or 100-μs delay. This delay in measuring the temperature sensitive parameter is set by an external switch. In the common-emitter circuit, the clock pulse also initiates a 4-μs delay, then reverses the states of transistors Q3 and Q4 to turn the I_B servo off and the V_{BB} measuring current supply on for a period of 110 μs, after which transistors Q3 and Q4 revert to their original state. In the common-base circuit, the inverted clock pulse turns the transistor Q2 on, shorting out the V_{EE} supply and causing the diode D1 to become nonconducting so that the only current across the emitter-base junction is the measuring current controlled by V_{BB}.

The common-base R_θ measuring circuit does not require the base switching logic which is used with the common-emitter configuration. Further, when measuring transistors with betas of 50 or more, the change in collector current as the collector voltage is varied is usually less than 1 percent; thus, the use of a constant-current servo in the base lead to control the collector current is not necessary. Both circuits have heating current and voltage capabilities of 0 to 2 A and 0 to 250 V, respectively.

Measurements of R_θ using both circuits were made on four 35-W, triple-diffused, silicon power transistors. The results of these preliminary measurements, given in table 2, indicate that there is substantial agreement between the two techniques. Further studies are needed to determine the relative merits of the two techniques when the transistor under test is operated under a wide variety of operating conditions.

An attempt was also made to make common-base R_θ measurements using the collector-base junction voltage as the temperature sensitive parameter. Problems were encountered with the sample-and-hold unit as well as with spurious signals affecting the voltage reading. A study was undertaken to determine what corrective measures should be taken to solve these problems. (F. F. Oettinger and S. Rubin)

Screen for Hot Spots — The use of d-c current gain, h_{FE}, as an indicator for the formation of hot spots and thermal hysteresis in power transistors has been discussed previously (NBS Tech. Note 520, pp. 49-52). In this technique, the base current, I_B, is measured as a function of power dissipated in the transistor while holding the collector current and case temperature constant. Under these conditions h_{FE} is proportional to the reciprocal of I_B. Hot-spot formation is indicated by a distinct increase in I_B with increasing power. The increase may be abrupt, as with constricted hot spots that exhibit thermal hysteresis, or more gradual, as may occur under higher current, lower voltage operating conditions. Typical examples are shown as solid curves in figure 11.

The effectiveness of the more commonly used base-emitter junction voltage, V_{BE}, as a screen for thermal instabilities [1] was compared with that of the base current. In the V_{BE} technique, the junction voltage is measured as a function of transistor power under conditions of constant collector current and case temperature. Typical results, shown as dashed curves in figure 11, indicate that while V_{BE} is sensitive to hot spots that exhibit thermal hysteresis it is relatively insensitive to the more amorphous, less constricted hot spot that occurs under higher current, lower voltage operating conditions. On the other hand, the I_B technique clearly indicates the formation of hot spots at high as well as low current levels.

The measurements described above were made in the common-emitter mode. Similar indications of the formation of hot spots and thermal hysteresis are obtained if I_B is measured in the common-base configuration. By comparing the common-emitter and common-base circuits, shown in figure 12 it can be seen that, as was the case with the common-base R_θ measuring circuit, the common-base h_{FE} circuit does not require a constant-current servo in the base lead to control the collector current as the collector voltage is varied. It is therefore evident that a production-oriented screening technique for hot-spot formation is feasible using the common-base h_{FE} circuit. (F. F. Oettinger and S. Rubin)

Table 2 — Comparison of Thermal Resistance Measured using Common-Emitter and Common-Base Circuits

Transistor	Common-Emitter	Common-Base
0-60	1.99°C/W	2.00°C/W
0-61	1.72	1.77
0-62	1.65	1.76
0-69	1.79	1.77

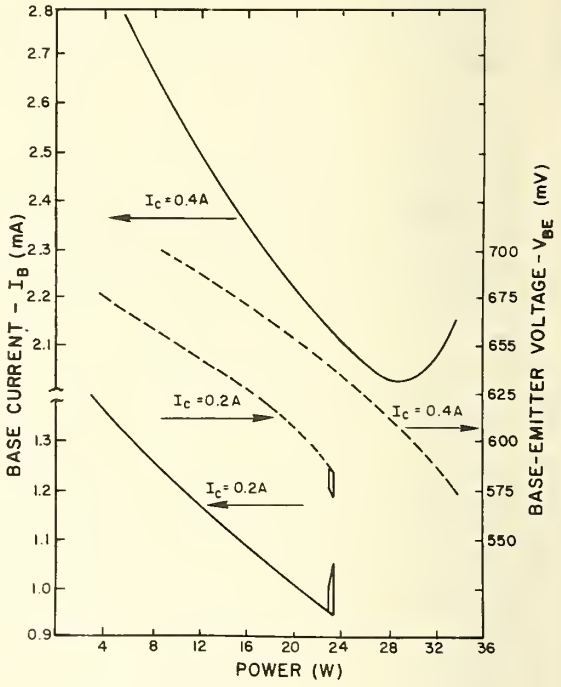
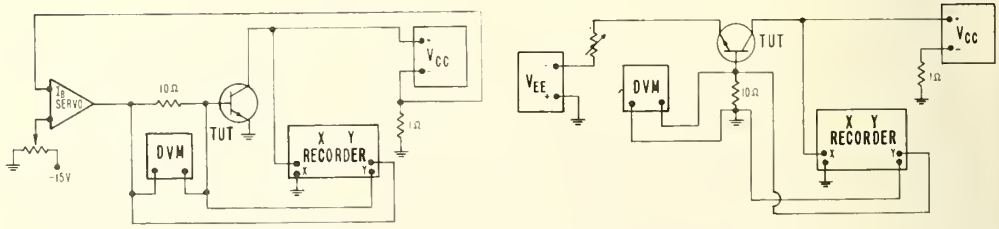


Figure 11. Base current (solid curves) and base-emitter voltage (dashed curves) as a function of power for a silicon power transistor showing onset of hot spots.



a. Common-emitter

b. Common-base

Figure 12. Circuits for measuring common-emitter current gain of transistors.

Thermal Hysteresis under Pulsed Operation — A study was undertaken to determine the pulse conditions (voltage transients or surges) under which a power transistor would be put into a constricted operating mode with thermal hysteresis. Both singly and repetitively pulsed collector excursions were performed with the common-base h_{FE} circuit. The voltage pulses were generated by utilizing the collector-switching transistor normally used with the common-base R_θ measuring circuit to short out a variable resistor in the collector circuit of the transistor under test. It was determined from the singly pulsed measurements that the transistor would go into thermal hysteresis if the collector voltage pulse had the proper combination of magnitude and width for a given starting point below the hot-spot initiation voltage. For example, a 20-V pulse, 5-ms wide caused a particular 35-W, triple-diffused, silicon power transistor to go into the constricted mode when the pulse was added to a d-c collector voltage level 6 V below the hot-spot initiation voltage. When the d-c collector voltage level was decreased to a point 12 V below the hot-spot initiation voltage the 5-ms wide pulse had to be increased to 30 V to cause a hot spot to form; a 10-V increase in pulse height is therefore required for a 6-V decrease in d-c collector voltage level. This nonlinear difference in energy needed to cause the device to go into thermal hysteresis might be explained by the fact that as the device operating point approaches the hot-spot initiation voltage it takes a proportionally smaller amount of energy to produce the needed temperature gradient due to that which already exists (NBS Tech. Note 592, pp. 49-51).

Work with repetitively pulsed collector voltage excursions demonstrated that hysteresis occurred when the product of the magnitude of the voltage pulse and the duty cycle equalled the steady-state change required to initiate hysteresis from a given collector voltage below the hot-spot initiation voltage. This was evidenced most clearly by the action of a moving coil voltmeter that was used to read the collector voltage. The voltage magnitude at which the device went into thermal hysteresis as indicated by the meter was the same for a d-c collector voltage as for a combined d-c and pulsed voltage. (S. Rubin and F. F. Oettinger)

Plans: The literature search and work on the bibliography on thermal resistance and transient thermal response measurements will be resumed. Design changes will be incorporated into the existing common-base R_θ measuring circuit to facilitate the use of the collector-base junction voltage as the temperature sensitive parameter for transistor thermal resistance measurements. Comparison of measurements made with this and other techniques for measuring R_θ will then be made. Work will also continue on the determination of the thermal inertia characteristics of the thermal hysteresis phenomenon. Thermographic measurements will be made on devices to investigate the relationships which may exist between the peak temperature on the chip and the electrically measured junction temperature.

5.2. THERMOGRAPHIC MEASUREMENTS

Objective: To evaluate the utility of thermographic techniques for detection of hot spots and measurement of temperature distribution in semiconductor devices.

Progress: An improved heat sink was fabricated to facilitate the calibration of the temperature sensitivity of the phosphors. The heat sink is suitable for calibrations in the temperature range 20 to 315°C which includes the temperature range of the three lowest temperature phosphors and the lower end of the temperature range of the highest temperature phosphor.

Further work was done with a slurry-settling technique for coating a specimen with phosphor. In this technique the specimen is placed in a slurry composed of 0.45 to 0.9 g of phosphor in 60 cm^3 of ethyl alcohol and the phosphor is allowed to settle onto the specimen surface for several minutes. The slurry is then drained and the specimen allowed to dry for 1.5 to 2 h while it is protected from air currents and kept at approximately room temperature. Preliminary results suggest that the thickness of the phosphor coating thus obtained can be controlled by controlling the depth beneath the surface at which the specimen is placed or by controlling the phosphor concentration in the slurry. The slurry-settling technique appears to give a more uniform phosphor coating than the water-floatation technique (NBS Tech. Note 488, p. 31), but conclusive experiments have yet to be made.

It was determined that the microcopy resolution chart (NBS Tech. Note 592, p. 56) used to establish the spatial resolution of the fiber-optic probe does not have strictly well defined white and black lines. Upon viewing the charts under a microscope (approximately 300 x magnification) a gray transition region between the black and white lines can be seen. The gray region consists of black dots randomly spaced on a white field; the density of dots decreases toward the center of the white line. For the smallest line width available on the test chart (0.028 mm), the dots extend across the entire width of the white line. This gray region may account for the apparently poor agreement between the spatial resolution of the 50-μm fiber-optic probe as determined with the aid of the microcopy resolution charts and the spatial resolution stated by the manufacturer. It has not yet been established whether it is possible, by accounting for the gray region, to determine the resolution of the fiber-optic probe by means of these charts.

Silicon wafers with surfaces of silicon dioxide, aluminum, gold, chromium, and polished silicon have been obtained for use in a study to establish coating uniformity and to determine whether a reaction occurs between the phosphors and the various surfaces.

(D. L. Blackburn and L. R. Williams)

Plans: The temperature calibration of the phosphors coated by the previously used water-floatation technique will be concluded. The proce-

dure for coating wafers and devices by the slurry-settling technique will be further developed to allow a controlled coating thickness to be obtained. If it is not feasible to use the microcopy resolution charts to establish the spatial resolution of the fiber-optic probe, metallization strips on a silicon substrate will be tested for this determination. Calibration and temperature sensitivity measurements on specimens coated by the slurry-settling technique will begin. Measurements will be made to establish the comparative uniformity of coatings made by the water-floatation and slurry-settling methods.

5.3. MICROWAVE DEVICE MEASUREMENTS

Objective: To study the problems and uncertainties associated with the measurement of selected microwave device properties, and to improve the techniques of these measurements.

Progress: To improve the precision of the low intermediate-frequency conversion-loss measurements, an incremental modulation technique has been introduced. With this technique, precision is limited principally by the resolution of the attenuator used to set the increment and by the mechanical stability of the waveguide system rather than by the output resolution.

In the new arrangement, the square-wave a-f generator used to modulate the local oscillator has been replaced by a stable d-c power supply. The change in r-f power caused by this d-c supply can be made identical to that caused by the square-wave generator. As before, power calculations are based upon sinusoidal modulation yielding the same peak and trough values. In effect, this change to incremental modulation reduces the intermediate frequency to zero. In addition to the advantage of using a more stable modulation source, this change also allows the use of a narrower signal bandwidth, which reduces system noise. It also allows the use of the precision rotary-vane attenuator, currently used to calibrate the PIN modulator, directly as the incremental modulator itself. A further advantage of incremental modulation is that the output voltage "peaks" can be read directly on a digital voltmeter, rather than by the more complex, less precise switched-oscilloscope d-c comparison method used with a-f modulation.

Incremental modulation has been used in the past for absolute mixer conversion loss measurements of the highest accuracy. As this method has been used [1], a microammeter is used to read an output current increment that occurs with an incremental change in power. The equation used to convert the current increment to conversion loss was not based on the modulation concept. In developing the periodic modulation method, commonly known as the modulation method, as an absolute rather than a relative method, it has become apparent that the incremental modulation method,

commonly known as the incremental method, remains the superior technique for high precision measurements. Now, however, the availability of precise digital voltmeters makes a method based on a voltage increment preferable to one based on a current increment. The equation used to convert the voltage increment is based on the modulation concept; this equation can be shown to be equivalent to the earlier one used with measurements of current increment.

Using a table of attenuation as a function of vane angle [2], it was calculated that the 0.0001-inch (2.5-μm) resolution of ordinary vernier micrometer heads used as adjustable stops to position the rotary-vane attenuator at precise locations should contribute less than 0.01 dB uncertainty to the conversion loss measurement. To obtain a commensurate accuracy, however, requires calibration of the attenuator to ±0.001 dB for a 1 dB modulation increment, which is several times better than can presently be obtained. Preliminary consideration was given to the use of a precision r-f power meter to establish the increment. To determine the increment within an uncertainty of ±0.001 dB requires independent power measurements within an uncertainty of ±0.0005 dB or ±0.01 percent of the power level. This is within the total bridge uncertainty (substituted d-c power, exclusive of voltmeter) of ±0.0061 percent reported [3] for the NBS Type II Power Measurement System for measurement of a power level of 10 mW using a 200-Ω, -12.3-Ω/mW thermistor. Bolometer instability appears likely to severely degrade this small uncertainty, so it is questionable that the use of a power meter to establish the increment would prove to be superior to the use of a calibrated attenuator. If the power meter were, in fact, superior, this would suggest that the attenuator calibration would be improved by using the same power meter.

An immediate limitation on precision is a lack of rigidity in the waveguide system. It was observed that the r-f power to the mixer is affected by mechanical forces on the waveguide. There is sufficient hysteresis in these power changes to suggest that interchanging the bolometer (mount) and the mixer (holder) or removing and reinserting a diode would result in a significant permanent power change. Although power changes may also result because of lack of reproducibility of diode contacts and position and of waveguide flange connections, these aspects of the problem cannot be investigated until the waveguide system is made more rigid.

(J. M. Kenney)

Plans: To facilitate use of the precision attenuator as the incremental modulator, it will be modified by the addition of precise mechanical stops (vernier micrometer heads with locks), a modification that is also required in order to improve the calibration accuracy beyond that possible using the relatively coarse dial. It will then be sent to NBS Boulder for calibration. A support system to add rigidity to the waveguide will be developed. A review of the current status of measurement requirements for microwave mixers will be undertaken to assure that task goals continue to be appropriate to these needs.

5.4. CARRIER TRANSPORT IN JUNCTION DEVICES

Objective: To improve methods of measurement for charge carrier transport and related properties of junction semiconductor devices.

Progress: The vector-voltmeter measurement system for measuring transistor delay time was assembled and preliminary tests were carried out. Two systems for the measurement of transistor S-parameters in the 200 to 800 MHz range are being assembled. An analysis of the equivalent circuits of a transistor in the Sandia-type bridge and in the vector-voltmeter circuit has been made to relate the measured delay time to various time constants and delay times within the device.

Experimental — A delay-time measurement circuit was constructed to interface between the transistor under test and a vector voltmeter. This allows measurements made using the Sandia-type bridge to be compared with those made using the completely independent, vector-voltmeter system. Preliminary measurements made with the vector-voltmeter on a silicon *n-p-n* transistor with f_α of about 350 MHz yielded delay times which were relatively independent of measurement frequency, as they should be, over the range 3 to 30 MHz. In order to resolve questions of absolute accuracy, a tiny R-C network of known delay time (423 ps) was assembled on a TO-18 transistor header. A spot measurement at 13 MHz on this network in the transistor socket yielded a measured delay time of 460 ps. This is within the specified accuracy of the vector voltmeter; greater accuracy requires the use of more refined techniques for calibration that are now being developed. The present approach is derived from the R-C network plug-in idea, and uses networks of known phase shift to calibrate the vector voltmeter to the accuracy needed for the transistor measurements. (D. E. Sawyer and F. R. Kelly)

Two systems are being assembled for the measurement of transistor S-parameters in the 200 to 800 MHz range. In both systems the r-f source is coupled to the transistor under test through a dual directional coupler and provisions are made to measure the amplitide and phase of both the signal reflected from the transistor terminals and the signal transmitted by the transistor. One system, being obtained commercially, is self-contained and requires only a bias supply and connections to the signal source and the device being measured. The second system is being assembled of individual components to provide an independent check on measurements made with the first. (G. J. Rogers)

Analytical — The equivalent circuits of a transistor in the Sandia-type bridge and in the common-base delay-time measurement circuit based on the use of a vector voltmeter have been analyzed to relate the measured delay time to the various time constants and delay times within the device. With the generally applicable measurement condition $\omega\tau_{vv} << 1$ prevailing, where ω is the test angular frequency and τ_{vv} the delay time obtained from the vector voltmeter, the transistor delay time expression simplifies to

$$\tau_{vv} = \tau_\alpha + \tau_e - \tau_c/h_{fe}.$$

In this equation τ_α is the delay time due to the transit of minority carriers across the base and collector junction regions, $\tau_e = r_e C_e$, and $\tau_c = r_b C_c$, where r_e is the small-signal emitter-base input resistance, r_b is the base resistance, C_e and C_c are the emitter-base and base-collector transition-region capacitances, respectively, and h_{fe} is the common-emitter small-signal current gain. Analysis of the Sandia-type bridge yields a similar delay-time equation except that correction factors appear as a consequence of the fact that for this bridge the signals applied to the transistor are obtained from quasi-voltage sources, and not from current sources, and so the transistor bridge input currents depend on the values of the transistor elements such as r_e and r_B. A memorandum is being written to record all the details of the analysis of these two measurement circuits so that applicable delay-time expressions can be obtained for a wide range of measurement conditions.

In considering the delay-time error that might be introduced into measurements made on the Sandia-type bridge by moving the primary loop in the attenuator and phase-splitter box relative to the two secondary coils (NBS Tech. Note 598, p. 40), it was concluded that this would not be a dominant source of error under present conditions of measurement.

(D. E. Sawyer)

Plans: Techniques for rapid, and accurate calibration of the Sandia-type bridge and the vector-voltmeter delay-time measurement equipment will be investigated. The memorandum relating measured delay times with device internal processes will be completed. Two systems for the measurement of delay time by means of S-parameter measurement will be set up. Measurements on the same transistors will be made by all four methods and the results compared.

5.5. SILICON NUCLEAR RADIATION DETECTORS

Objective: To conduct a program of research, development, and device evaluation in the field of silicon nuclear radiation detectors with emphasis on the improvement of detector technology, and to provide consultation and specialized device fabrication services to the sponsor.

Progress: The studies of radiation damage effects of 600-keV electrons and fast neutrons in lithium-drifted silicon detectors have been completed. The effects of exposure of a silicon surface-barrier detector to dry ammonia and methanol vapor at various pressures have been studied.

Testing and Evaluation — Testing of commercial lithium-drifted silicon detectors for evaluation before acceptance by the sponsor has been concluded. These pre-flight bench-tests were carried out at the NASA-GSFC site for the IMP-H and Pioneer-F programs. (A. J. Baroody)

Radiation Damage — A commercial, 2-mm thick, lithium-drifted silicon detector was irradiated with 600-keV electrons at fluences between 1×10^{12} and 5×10^{15} cm^{-2} on the particle entrance window (*p*-contact). The irradiation was carried out at room temperature and with an applied detector bias of 400 V. The average range of electrons of this energy in silicon is approximately 850 μm; therefore, defects are expected to be localized in the region extending from the entrance window to a depth of approximately 640 μm [1]. Damage effects similar to those observed using 1.5 meV electrons were seen (NBS Tech. Note 598, pp. 41-42), but to a lesser extent. After irradiation at a fluence of 5×10^{15} cm^{-2}, a dead layer approximately 600 μm thick was observed at a bias of 400 V at the irradiated *p*-contact. No change in detector response was observed when counting particles incident on the unirradiated rear contact.

A second detector was irradiated through the rear *n*-contact under the same conditions as above. The results indicated that the increase of noise with increased fluence was much faster than that obtained from front *p*-contact irradiation while the variation in current was about the same.

Two detectors were irradiated at room temperature with fast neutrons from a calibrated plutonium-beryllium neutron source. One detector was reverse-biased at 400 V; the other, at 100 V. With the detectors located 5 cm from the source, the neutron flux is approximately 5×10^4 cm^{-2} s^{-1}. The gamma-ray background was small and damage effects due to gamma rays could be neglected. Fast neutron irradiation produces many secondary interactions in silicon because the energy acquired by the silicon atoms from elastic neutron collisions is quite high. Dearnaley [2] has estimated that each neutron-silicon atom collision produces a minimum of 150 Frenkel pairs. Such interactions are characterized by small, highly-damaged regions of complex defect clusters separated by considerable amounts of undamaged material due to the large mean free path between collisions. The degradation of detector performance observed due to neutron damage was similar to that observed in the charged particle irradiations with significant increases in noise and current above fluences of 10^{10} cm^{-2}. After the final irradiation at a neutron fluence of approximately 6×10^{10} cm^{-2}, a dead layer of about 40 μm was evident on the irradiated front contacts of both detectors. This result indicates that the pulse-height defect was relatively independent of bias. The increase in noise and current with increased fluence was faster at the higher bias. Annealing effects have not been observed during a two week period following the irradiation. (Y. M. Liu)

Ambient Exposure Tests — The effects of exposure of dry ammonia and methanol vapor on the noise of a silicon surface-barrier detector were measured. The detector was placed in the vacuum manifold and pumped at 0.06 mTorr for 24 hours before dry ammonia was admitted into the test chamber. The detector noise level as measured using an oscilloscope and RMS voltmeter [3] varied from 33.5 to 39.7 keV before the tests were begun.

Dry ammonia was leaked into the system through a variable micro-leak valve and unless otherwise noted, the system was maintained at pressure for 5 min before noise level measurements were made. Four measurements were made at pressures from 0.03 to 0.7 mTorr; detector noise remained fairly constant at 39.1 keV. Twenty measurements were made at pressures from 1 to 100 mTorr; noise varied from 39.3 keV to 40.9 keV. The ammonia pressure was held at 5 mTorr for 2 h; noise varied between 39.3 to 40.1 keV At the end of the 100 mTorr run, the pressure was lowered to 50 mTorr and held there for 17 h; the noise level of the detector changed from 40.1 to 37.7 keV. The system was then pumped down to 0.03 mTorr overnight, and tests were subsequently made from 100 to 1000 mTorr in six steps, holding for 5 min at each step. The noise level remained near 36.9 keV.

Methanol exposure tests were run in a manner similar to the ammonia runs. The spectro-grade methanol source consisted of a reservoir of the solvent fed directly to the face of the leak valve. Ten measurements were made at pressures ranging from 0.05 to 100 mTorr; detector noise levels ranged from 36.2 to 36.9 keV. The pressure was held at the 1000 mTorr level for 2 h with no change in noise. (W. K. Croll)

Plans: The study of 2-MeV proton radiation damage effects in lithium-drifted silicon detectors will be completed. Detectors irradiated with electrons, neutrons, and protons will be studied by means of the infrared response technique in order to seek correlation between the results observed and energy levels introduced into the silicon by irradiation. Ambient exposure tests will be carried out on lithium-drifted silicon detectors supplied by the sponsor. Dry ammonia, methanol, and commerical leak detector fluid will be used.

5.6. REFERENCES

5.1. Thermal Properties of Devices

1. Scarlett, R. M., Shockley, W., and Haitz, R. H., Thermal Instabilities and Hot Spots in Junction Transistors, *Physics of Failure in Electronics*, M. F. Goldberg and M. Vaccaro, Eds. (Spartan Books, Inc., Baltimore, Md., 1963), pp. 194-203.

5.3. Microwave Device Measurements

1. Method 4101.3, Conversion Loss, Test Method A (Incremental), MIL-STD-750B, Test Methods for Semiconductor Devices, Notice 1, 13 May 1970.

2. Larson, W., Table of Attenuation as a Function of Vane Angle for Rotary-Vane Attenuators ($A = -40 \log_{10} \cos \theta$), NBS Tech. Note 229 (Jan. 7, 1965); see also Larson, W., Table of Attenuation Error as a Function of Vane-Angle Error for Rotary Vane Attenuators, NBS Tech. Note 177 (May 20, 1963).

3. Design Package Available for NBS RF Power Measurement System, *NBS Tech. News Bull.* 55, 117 (1971).

5.5. Silicon Nuclear Radiation Detectors

1. Liu, Y. M., and Coleman, J. A., Electron Radiation Damage Effects in Silicon Surface-Barrier Detectors, *IEEE Trans. Nucl. Sci.* NS-18, No. 1, 192-199 (1971).

2. Dearnaley, G., and Northrop, D. C., Semiconductor Counters for Nuclear Radiations, (E. & F. N. Spon Ltd., London, 1964), pp. 268-269.

3. USA Standard and IEEE Test Procedure for Semiconductor Radiation Detectors (for Ionizing Radiation), USAS N42.1(1969)/IEEE No. 300, pp. 5-6.

Appendix A

JOINT PROGRAM STAFF

Coordinator: J. C. French
Consultant: C. P. Marsden

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Appendix B

COMMITTEE ACTIVITIES

ASTM Committee F-1 on Electronics
- A. J. Baroody, Lifetime Section
- C. F. Bolton, Committee Assistant Secretary
- W. M. Bullis, Editor, Subcommittee 4, Semiconductor Crystals, and Subcommittee 7, Hybrid Microelectronics; Leaks, Resistivity, Mobility, Dielectrics, and Compound Semiconductors Sections
- J. A. Coleman, Secretary, Subcommittee 5, Semiconductor Processing Materials
- J. R. Ehrstein, Chairman, Resistivity Section, Epitaxial Resistivity, and Epitaxial Thickness Sections
- J. C. French, Committee Editor
- G. G. Harman, Bonding Section
- K. O. Leedy, Chairman, Bonding Section
- T. F. Leedy, Photoresist Section
- C. P. Marsden, Committee Secretary
- R. L. Mattis, Lifetime Section
- W. E. Phillips, Chairman, Lifetime Section; Secretary, Subcommittee 4, Semiconductor Crystals; Crystal Perfection, Encapsulation, Thin Films, and Thick Films Sections
- A. H. Sher, Germanium Section
- W. R. Thurber, Mobility, Germanium, Compound Semiconductors, and Impurities in Semiconductors Sections

ASTM Committee E-10 on Radioisotopes and Radiation Effects
- W. M. Bullis, Subcommittee 7, Radiation Effects on Electronic Materials
- J. C. French, Subcommittee 7, Radiation Effects on Electronic Materials

Electronic Industries Association: Solid State Products Division, Joint Electron Device Engineering Council (JEDEC)
- J. M. Kenney, Microwave Diode Measurements, Committee JC-21 on UHF and Microwave Diodes
- F. F. Oettinger, Chairman, Task Group JC-11.3-1 on Thermal Considerations for Microelectronic Devices, Committee JC-11 on Mechanical Standardization; Technical Advisor, Thermal Resistance Measurements; Committees JC-22 on Thyristors, JC-20 on Signal Diodes, JC-25 on Power Transistors, and JC-30 on Hybrid Integrated Circuits
- S. Rubin, Chairman, Council Task Group on Galvanomagnetic Devices
- H. A. Schafft, Technical Advisor, Second Breakdown and Related Specifications, Committee JC-25 on Power Transistors

IEEE Electron Devices Group:
- J. C. French, Standards Committee
- J. M. Kenney, Chairman, Standards Committee Task Force on Microwave Solid State Devices II (Mixer and Video Detector Diodes)

H. A. Schafft, Chairman, Standards Committee Task Force on Second Breakdown Measurement Standards

IEEE Nuclear Science Group:
J. A. Coleman; Administrative Committee; Nuclear Instruments and Detectors Committee; Editorial Board, *Transaction on Nuclear Science*

IEEE Magnetics Group
S. Rubin, Chairman, Galvanomagnetic Standards Subcommittee

IEEE Parts, Hybrids, and Packaging Group
W. M. Bullis, New Technology Subcommittee, Technical Committee on Hybrid Microelectronics

Society of Automotive Engineers
J. C. French, Subcommittee A-2N on Radiation Hardness and Nuclear Survivability
W. M. Bullis, Planning Subcommittee of Committee H on Electronic Materials and Processes

IEC TC47, Semiconductor Devices and Integrated Circuits:
S. Rubin, Technical Expert, Galvanomagnetic Devices; U. S. Specialist for Working Group 5 on Hall Devices and Magnetroresistive Devices

NMAB ad hoc Committee on Materials and Processes for Electron Devices
W. M. Bullis

NMAB ad hoc Committee on Materials for Radiation Detection Devices
D. E. Sawyer

Appendix C

SOLID-STATE TECHNOLOGY & FABRICATION SERVICES

Technical services in areas of competence are provided to other NBS activities and other government agencies as they are requested. Usually these are short-term, specialized services that cannot be obtained through normal commercial channels. Such services provided during the last quarter are listed below and indicate the kinds of technology available to the program.

1. Radiation Detectors (W. K. Croll and J. Krawczyk)
   Five lithium-drifted silicon detectors measuring 50 by 20 by 0.75 mm and divided by 0.38 mm wide ultrasonically-machined slots into 12 parallel active regions measuring 46 by 1.5 mm were fabricated for the Electronuclear Physics Section for use in an electron-scattering hodoscope.

2. Thin-Film Deposition (T. F. Leedy)
   Thin-film silver contacts were vacuum evaporated on piezoelectric polymer sheets for the Instrumentation Applications Section.

3. Capacitor Fabrication (T. F. Leedy)
   Three quartz guard ring capacitors were fabricated for the Pressure Measurements Section. Each capacitor consisted of a quartz disc 1.5 cm in diameter by 2 mm thick. Aluminum contacts were applied to each face and the edge. Guard rings were photolithographically defined in the faces of the disc so that three-terminal capacitance measurements can be made.

Appendix D

JOINT PROGRAM PUBLICATIONS

Prior Reports:

A review of the early work leading to this Program is given in Bullis, W. M., Measurement Methods for the Semiconductor Device Industry—A Review of NBS Activity, NBS Tech. Note 511, December, 1969.

Quarterly reports covering the period since July 1, 1968, have been issued under the title Methods of Measurement for Semiconductor Materials, Process Control, and Devices. These reports may be obtained from the Superintendent of Documents (Catalog Number C.13.46:XXX) where XXX is the appropriate technical note number. Microfiche copies are available from the National Technical Information Service (NTIS), Springfield, Virginia 22151.

Quarter Ending	NBS Tech. Note	Date Issued	NTIS Accession No.
September 30, 1968	472	December, 1968	AD 681330
December 31, 1968	475	February, 1969	AD 683808
March 31, 1969	488	July, 1969	AD 692232
June 30, 1969	495	September, 1969	AD 695820
September 30, 1969	520	March, 1970	AD 702833
December 31, 1969	527	May, 1970	AD 710906
March 31, 1970	555	September, 1970	AD 718534
June 30, 1970	560	November, 1970	AD 719976
September 30, 1970	571	April, 1971	AD 723671
December 31, 1970	592	August, 1971	AD 728611
March 31, 1971	598	October, 1971	

Current Publications:

Rubin S., and Oettinger, F. F., Thermal Hysteresis and its Possible Effect on Restriction of the Hot-Spot Free Operating Range of Some Power Transistors, *IEEE Trans. Electron Devices* ED-18, 393-394 (June, 1971).

Harman, G. G., and Kessler, H. K., Application of Capacitor Microphones and Magnetic Pickups to the Tuning and Trouble Shooting of Microelectronic Ultrasonic Bonding Equipment, NBS Tech. Note 573, April, 1971.

Sher, A. H., and Thurber, W. R., Minority Carrier and Lithium-Ion Drift Mobilities and Oxygen Concentration in *p*-Type Germanium, to be published in *J. Appl. Phys.* (September, 1971).

Sher, A. H., Croll, W. K., and Thurber, W. R., Determination of Oxygen in Germanium Below 20 ppb by Measurements of Lithium Mobility and Precipitation, to be published in *Anal. Chem.* (November, 1971).

Brenner, D. J.,* A Technique for Measuring the Surface Temperature of Transistors by Means of Fluorescent Phosphor, NBS Tech. Note 591, July, 1971.

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* NBS Measurement Engineering Division

APPENDIX E

STANDARDIZATION AND DISSEMINATION ACTIVITIES

(A summary for fiscal year 1971)

STANDARDS ACTIVITIES:

- Interim standards
- ASTM editorial review (15 documents)
- Verification of standards
- Round robin experiments

  ASTM (F-1) 5 methods
  EIA (JEDEC: JC-22, 25) 3 methods

- Committee participation

  ASTM (F-1, E-10)
  EIA (JEDEC: JC-11, 20, 21, 22, 24, 25, 30)
  IEC (TC-47)
  IEEE (G-ED, MAG, MTT, NS, PHP)
  NMAB
  SAE (A2N, H)

  About 20 staff members active
  About 15 offices held by staff members
  Over 50 task forces or committees attended

  Benefits are (1) guidance to program, (2) rapid utilization of results by industry

FIELD VISITS: 54 to industrial, university, and government installations

PUBLICATIONS AND TALKS: 22; in addition QPR's go by request to nearly 600 persons on initial distribution

VISITS TO NBS: About 75 formal; 105 for specific information exchange

CONSULTATIONS: 170

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16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

This quarterly progress report, twelfth of a series, describes NBS activities directed toward the development of methods of measurement for semiconductor materials, process control, and devices. Significant accomplishments during this reporting period include a demonstration of the high sensitivity of the infrared response technique by the identification of gold in a germanium diode doped to a level of 10^{11} gold atoms per cubic centimeter, verification that transient thermal response is significantly more sensitive to the presence of voids in die attachment than steady-state thermal resistance, and development of a simplified circuit for screening transistors for susceptibility to hot-spot formation by the current-gain technique. Work is continuing on measurement of resistivity of semiconductor crystals; study of gold-doped silicon; specification of germanium for gamma-ray detectors; evaluation of wire bonds and die attachment; measurement of thermal properties of semiconductor devices, transit time and related carrier transport properties in junction devices, and electrical properties of microwave devices; and characterization of silicon nuclear radiation detectors. Supplementary data concerning staff, standards committee activities, technical services, and publications are included as appendixes.

Key Words (cont.): microelectronics; microwave devices; nuclear radiation detectors; probe techniques (a-c); resistivity; semiconductor devices; semiconductor materials; semiconductor process control; silicon; thermal resistance; thermographic measurements; ultrasonic bonder; wire bonds.

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